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Impact of tropical cyclone track change on regional air quality

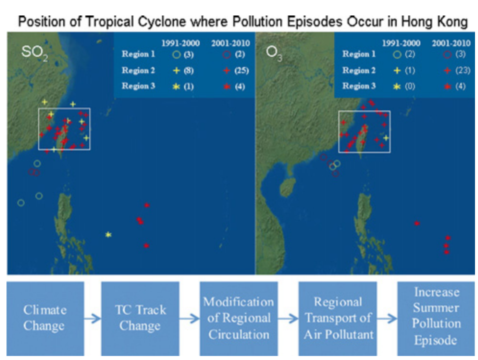
Yun Fat Lam [a,b,*], Hung Ming Cheung [a,c], Chi Cheong Ying [a]

[a] School of Energy and Environment, City University of Hong Kong, Hong Kong
[b] Guy Carpenter Asia-Pacific Climate Impact Centre, City University of Hong Kong, Hong Kong
[c] School of Earth and Environmental Sciences, Seoul National University, Seoul, Republic of Korea

HIGHLIGHTS

- Under the influence of climate change,TC track changes in the western North Pacific have potential impact on regional air quality in South China.
- TCs in the vicinity of Taiwan have the highest impact on HK air quality due to transport of pollutants from PRD, leading to higher chances of episodes.
- While the impact on SO_2 is diminishing, the impact on O_3 is intensifying due to the effects of global climate change, and precursor's enhancement.
- If the prevailing track change towards the Taiwan region persists, the occurrence of TC-related O_3 episodes in Hong Kong will increase.

GRAPHICAL ABSTRACT



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ABSTRACT

There has been an increase in tropical cyclones (TCs) in the western North Pacific (WNP) that traverse with a northward recurving track towards East Asia and a decrease in TC tracks entering the South China Sea (SCS) in the past few decades. To investigate the potential impact of the prevailing TC track change on Hong Kong air quality, an analysis has been carried out based on historical data (1991 to 2010) of TC tracks and air quality. Compared to TCs in other regions, TCs in the vicinity of Taiwan (Region 2, R2) have the greatest impact on Hong Kong air quality due to regional transport of air pollutants from the highly industrialized Pearl River Delta (PRD). In the last twenty years, the number of days with TCs in R2 (May to October) has increased by 45% from 111 days in the period 1991–2000 to 161 days in 2001–2010, during which there was an increase in yearly TC-related pollution episodes of approximately 3 episodes per year in Hong Kong. The enhancement of mean O_3 concentration due to TCs in R2 is reported as 82% (~50.8 μg/m^3 at a rural station) and 58% (~16.8 μg/m^3 at an urban station) higher than the summer averages. A similar enhancement is also observed for PM_{10} (called RSP) and SO_2 with an average of 70% (i.e., 22.2 μg/m^3) and 100% (i.e., 15.2 μg/m^3) increases, respectively. Overall, the 20 years of historical data show that the O_3 concentrations on the TC-affected days are increasing at the estimated rates of 0.5 μg/m^3 and 2.6 μg/m^3 per year, respectively, in the urban and remote areas, which are significantly higher than the increase of 0.3 μg/m^3 and 0.4 μg/m^3 per year in the average summer concentrations.

Abbreviations: PRD, Pearl River Delta; HK, Hong Kong; TC, tropical cyclone; SCS, South China Sea; HKEPD, Hong Kong Environmental Protection Department; HKO, Hong Kong Observatory; WNP, western North Pacific; TM, Tap Mun.

* Corresponding author at: School of Energy and Environment, City University of Hong Kong, Hong Kong.
E-mail address: yunflam@cityu.edu.hk (Y.F. Lam).

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1. Introduction

Hong Kong (HK) air quality has deteriorated in recent years due to the regional transport of air pollutants from the rapid industrialization of the Pearl River Delta (PRD). According to the Hong Kong Environmental Protection Department, autumn and winter account for 67% of air pollution episodes, while summer accounts for 26% of episodes (HKEPD, 2016). Previous studies showed that tropical cyclones (TCs) approaching HK have significant impacts on local air quality as TCs produce a reversal of wind direction (from the southwesterly to northerly, westerly or northwesterly wind), which results in the transport of air pollutants from PRD to HK. This is similar to the effect of northeasterly monsoon that occurs in autumn and winter (Lee and Savtchenko, 2006; Feng et al., 2007; Huang et al., 2006; Yang et al., 2012; Lam, 2017). When TCs are hovering in the western North Pacific (WNP) near the Luzon Strait or in the vicinity of Taiwan, the subsidence of airflow on their periphery creates temperature inversion and stagnation (low wind condition) which inhibit the dispersion of air pollutants in South China (Lam and Lau, 2005; Huang et al., 2009; Yang et al., 2012; Kwok et al., 2017), resulting in accumulation of pollutants that increase the severity of TC-related air quality episodes. Similar air quality influence from TCs has also been found in the Malaysia peninsula (Oozeer et al., 2016).

Many high particulate matter (PM) and ozone (O_3) episodes have been reported under the influence of TCs for HK over the past two decades. These episodes have been noted to have higher O_3 concentration compared to the late autumn and winter episodes, as the intense sunlight under the large-scale subsidence with high temperature encourages the photochemical formation and accumulation of O_3 (Lee et al., 2002; So and Wang, 2003; Lam et al., 2005; Wei et al., 2016). Huang et al. (2009) and Zhang et al. (2013) reported that the top 33% percentile of O_3 episodes in HK is associated with TC events, and there is an observed increase of O_3 episodes in recent years (HKEPD, 2016). Wu et al. (2005) and Tu et al. (2009) found that more TCs were entering the Luzon Strait or Taiwan from the western North Pacific (WNP) in the last decade. This is linked to the observed increase in northward recurving TC tracks towards East Asia with a decrease in the westward track towards the South China Sea (SCS) (Tu et al., 2009). The shift of TC track is found to be associated with the change of global sea-surface temperature (SST) and the associated changes in the WNP subtropical ridge of high pressure and large-scale steering flows (Ho et al., 2004; Wu and Wang, 2004; Wu et al., 2005; Goh and Chan, 2010). In addition, it may also be related to global warming or climate change, as Wang et al. (2011) reported that the prevailing TC track change to Luzon Strait may continue until year 2040 under the A1B scenario of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007). This suggests the possibility that climate change may have an impact on the regional air quality through its influence on TC tracks in the future.

As meteorological conditions resulting from different TC positions are significant to the occurrence of pollution episodes in HK, understanding the TC track change in recent decades is important. In this study, a systematic analysis on the impact of changes in TC positions on HK air quality was performed using historical data (i.e., 1991 to 2010) to establish the relationship between the TC position and pollutant concentration. The focus of this study is on the summer months (May, June, July and August) where the influence of northeasterly monsoon on regional air quality is minimal. The characteristics and magnitudes of the impacts in different regions (i.e., region 1, 2 and 3, which is defined later) were analyzed with reference to the changes of pollutant concentrations (i.e., SO_2, PM_{10} and O_3) for a better understanding of the influence of TC track change on summer pollution episodes in South China.

2. Material and methods

In order to investigate the change of TC track in recent years using historical data, we have selected year 2000 as our dividing point. The selection of year 2000 was made based on considerations of data availability (the study was first developed in 2012) and the corresponding historical period of the IPCC AR4 scenario (IPCC, 2007). As a result, the study period is divided into two epochs: (1) May to October of 1991 to 2000 and (2) May to October of 2001 to 2010. All TC track and air quality data were collected from the Hong Kong Observatory (HKO) and the Hong Kong Environmental Protection Department (HKEPD). The detailed discussion of these datasets is described below.

2.1. Tropical cyclone data from Hong Kong observatory

The track information (e.g., latitude/longitude position), maximum sustained wind speed and pressure of the storm center for all TCs formed in the WNP and SCS are available in the annual tropical cyclone publication (HKO, 2012). The publication covers various categories of TC systems including tropical depression, tropical storm, severe tropical storm, typhoon, severe typhoon and super typhoon. It recorded the entire TC track from its formation to its landfall/dissipation. In Hong Kong, majority of TCs occurs between May and October. In this study, we collected 6-hourly TC track data with latitude and longitude information from 1991 to 2010 for May to October. The track data was then incorporated into a 2.5° × 2.5° gridded format to generate a TC track density map. The track density is defined as the summation of all TCs in the period divided by number of years (i.e., 10 years). Each 0.1 increment of TC track density corresponds to a single TC event. Fig. 1 shows the difference in TC track density between those two epochs (second minus

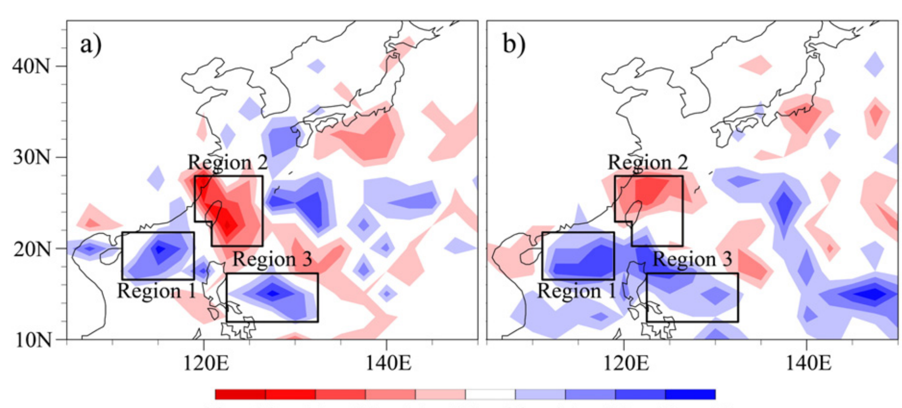

Fig. 1. TC track density difference between 2001–2010 and 1991–2000: a) summer (May–August), and b) autumn (September–October). Region 1, 2 and 3 are bounded from 16.5N to 22.0N, and 111.0E to 119.0E, 20.0N to 28.0N, and 119.0E to 126.5E, and 12.0N to 17.0N, and 112.5E to 132.5E, respectively.

first). It is clear that there is a decrease in the number of TCs entering the SCS and the Philippines Sea (blue color) and an increase in track density in the vicinity of Taiwan (red color) for both summer and autumn. These results are consistent with the northward shift of TC tracks reported in the literature (Wu et al., 2005; Tu et al., 2009; Wang et al., 2011). In order to further understand the impacts of TC track change on local air quality from 1st epoch to 2nd epoch, we subdivided the position of TC tracks into three separate regions: SCS region (Region 1, R1), Taiwan region (Region 2, R2), and the Philippines Sea (Region 3, R3), as shown in Fig. 1. These boxes were defined based on the combination of TC positions when pollution episodes occur (see graphical abstract), and an arbitrary threshold of ± 0.8 on the difference in TC track density between the two epochs (see Fig. 1).

2.2. European reanalysis-interim (ERA-Interim) data

The ERA-Interim dataset from 1991 to 2010 was used to analyze the large-scale circulation when TCs entered those three regions (See Fig.1). Parameters such as wind direction and vertical velocity were adopted to understand the vertical and horizontal circulations induced by TCs in the regions. The ERA-Interim data is a global climate reanalysis dataset that uses European Center for Medium-Range Weather Forecasts (ECMWF) model with 4-dimensional variation analysis (4D-Var) to generate 6-hourly atmospheric and 3-hourly surface fields. It contains the spectral resolution of T255 (80 km horizontal resolution) with 60 vertical levels from the surface up to 0.1 hPa (Dee et al., 2011).

2.3. Air pollution data from Hong Kong environmental protection department

The Hong Kong air quality observation network was established in early 1990 by HKEPD, as an effort to protect public health and to understand the ambient air quality in HK. The network was first established with 7 stations including Central Western, Kwai Chung, Kwun Tong, Sham Shui Po, Shatin, Tai Po and Mong Kok. It measures hourly SO_2, NO_2, NOx, CO, Total Suspended Particulate (TSP) and O_3. Respirable Suspended Particulates (RSP), more commonly referred to as PM_{10}, was introduced in 1995 to strengthen the local PM measurements. RSP is defined as particulate matters sized < 10 μm in diameter. Currently, 15 stations (i.e., 12 ambient stations and 3 roadside stations) are in operation, in which 9 of them were non-compliance with the existing air quality standards (HKEPD, 2015). In general, the non-compliances in these stations were related to the exceedances of 24-h RSP and annual NO_2 standards for roadside stations, and 24-h RSP and 8-h O_3 standards for ambient stations. In this study, we selected two distinct ambient monitoring stations: Kwai Chung (KC) and Tap Mun (TM), as shown in Fig. 2a. KC station is located in a highly polluted/urbanized area near the Kwai Chung Container Terminal with the longest monitoring records. It covers the period from 1991 to 2010 for SO_2 and O_3 and a shorter period from 1995 to 2010 for RSP. The selection of this station is used for understanding local pollution trends in the past two decades under the influence of TCs. TM station is a regional background station located at the far eastern side of HK (away from all major emission sources) on a remote island. It covers the data from 1998 to 2010 for RSP, SO_2 and O_3 and is intended to be used for understanding the effect of regional transport of air pollutants into HK in recent years. Please note that no $PM_{2.5}$ data is available on those stations during the targeted period as the monitoring network of $PM_{2.5}$ was established in 2011 (HKEPD, 2012).

3. Results and discussion

3.1. Comparisons on local meteorological influence from TCs

Based on the ERA-Interim data, the composite horizontal and vertical wind at 1000 hPa during the period 1991 to 2010 is plotted in Figs. 2b and 3a–c. Comparing with the prevailing southwesterly flow in summer (Fig. 2b), TCs are clearly influencing the regional circulation (see the red arrows in Fig. 3a–c), and depending on the TC position, the effect on the wind direction in HK could be quite different. For example, when TCs are in R1 and R3, HK is mainly downwind of the oceanic southeasterly wind, with a lower wind speed for TCs in R3 due to weaker TC influence. On the other hand, when TCs are in R2, the wind direction changes to northerly/northwesterly and puts HK at the downwind direction of PRD with weak wind. In terms of vertical velocity, a sinking airflow (shown in red) on HK has been observed under the influence of TCs in R2, in contrast with the upward direction (shown in blue) over HK for TCs in R1 and R3. As the composite vertical velocity is found by averaging all TC days from 1991 to 2010 for each region, this can only be interpreted as having weaker subsidence of airflow for TCs in R1 and R3 than TCs in R2 in general. The result does not reflect the actual vertical motion of individual TCs.

3.2. Comparisons of local air quality for TCs at different regions

To understand the local air quality on the TC-affected days, the cumulative distribution functions (CDF) of daily average RSP, daily average SO_2 and maximum daily average 8-h (MDA8) O_3 concentrations at TM and KC stations for summer are shown in Fig. 4. The "all summer days" curve (black color) represents the overall distribution of the concentrations in the summer (May to August) regardless of TC occurrence. The values on the right hand corner represent the mean concentration of "all summer days" (black), R1 (green), R2 (red) and R3 (blue), and the percentage differences between mean concentrations for each region (R1, R2 and R3) and "all summer days" means are stated inside the parentheses. For TM station (Fig. 4a–c), the CDF curves of RSP, SO_2 and MDA8 O_3 for days with TCs in R1 and R3 are approximately the same as the "all summer days" curves, with +1% to +7% change in

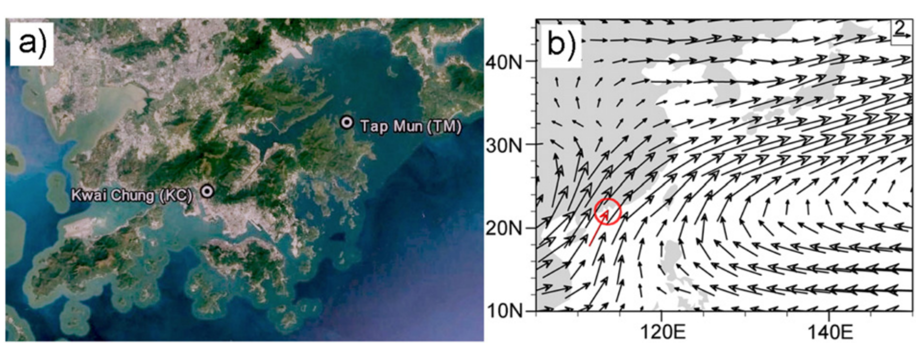

Fig. 2. a) Locations of selected HKEPD monitoring stations: Kwai Chung (KC) and Tap Mun (TM); b) Composite wind at 1000 hPa in summer for non-TC condition from ERA-Interim data (red circle indicates the position of HK, and red arrow signifies the prevailing wind direction).

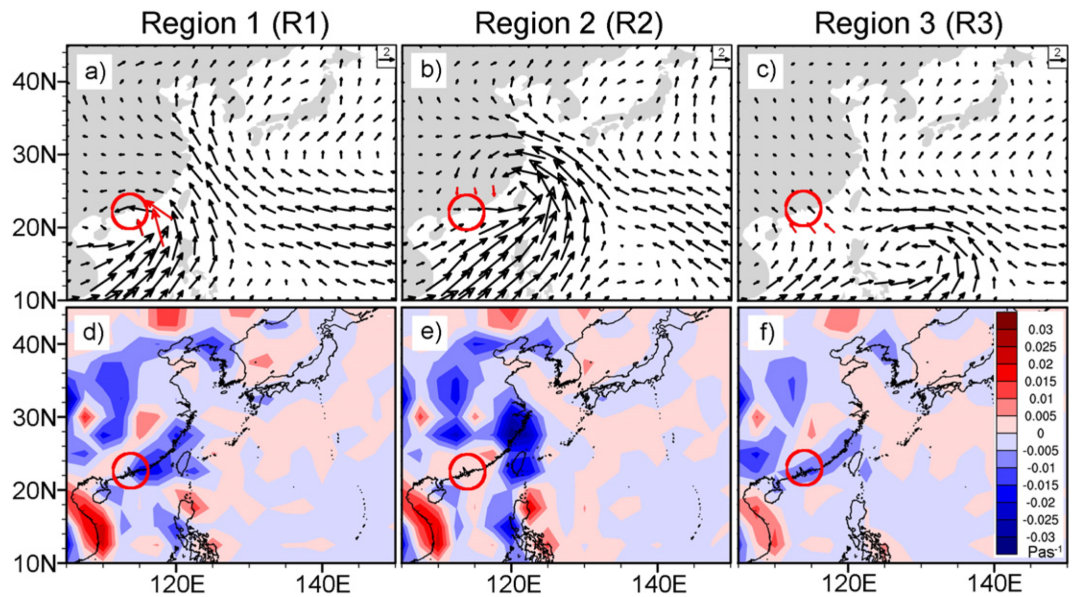

Fig. 3. Composite of horizontal wind at 1000 hPa when TCs are in (a) R1, (b) R2, and (c) R3, and vertical velocity (omega) in Pa s^{-1} at 1000 hPa when TCs are in (d) R1, (e) R2, and (f) R3. Positive values (red) indicate downdrafts motion. Red circles indicate the position of HK, and red arrows signify the prevailing wind direction over HK under the influence of TCs in different regions.

the mean concentrations. The similar/overlapping CDF pattern reveals that TM station receives very limited pollution impact from the PRD emissions under the southerly wind. The average mean concentrations of RSP, SO_2 and MDA8 O_3 (average of R1 and R3) are reported as ~28.7 μg/m^3, ~9.4 μg/m^3 and ~78.0 μg/m^3, respectively, which are much lower than the World Health Organization (WHO) air quality guidelines (AQG) of daily average RSP of 50 μg/m^3, daily average SO_2 of 50 μg/m^3 (Interim target-2), and MDA8 O_3 of 100 μg/m^3 (WHO, 2006). On the other hand, for KC station (Fig. 4d–f), the CDF curves for TCs in R1 and R3 are both shifted to the lower side (to the left) for RSP and SO_2 with mean differences of −5% to −49%, while slightly to the higher side (to the right) for MDA8 O_3 with mean differences of +8% to +42% compared with "all summer days". The higher CDF of RSP and SO_2 in "all summer days" is mainly caused by the channel effect induced by the hilly terrain on the southwesterly wind passing through the Victoria Harbor, which drives emissions from the coastal PRD (e.g., local marine vessel in western HK, Macao, and Zhuhai) to the western part of HK (i.e., non-TC condition, see Fig. 2b), resulting in higher marine background concentrations in "all summer days" than in R1 and R3. Compared with TM station, KC station is located nearby the container port and is often affected by port emissions, so the average mean RSP and SO_2 concentrations (average of R1 and R3) are much higher than

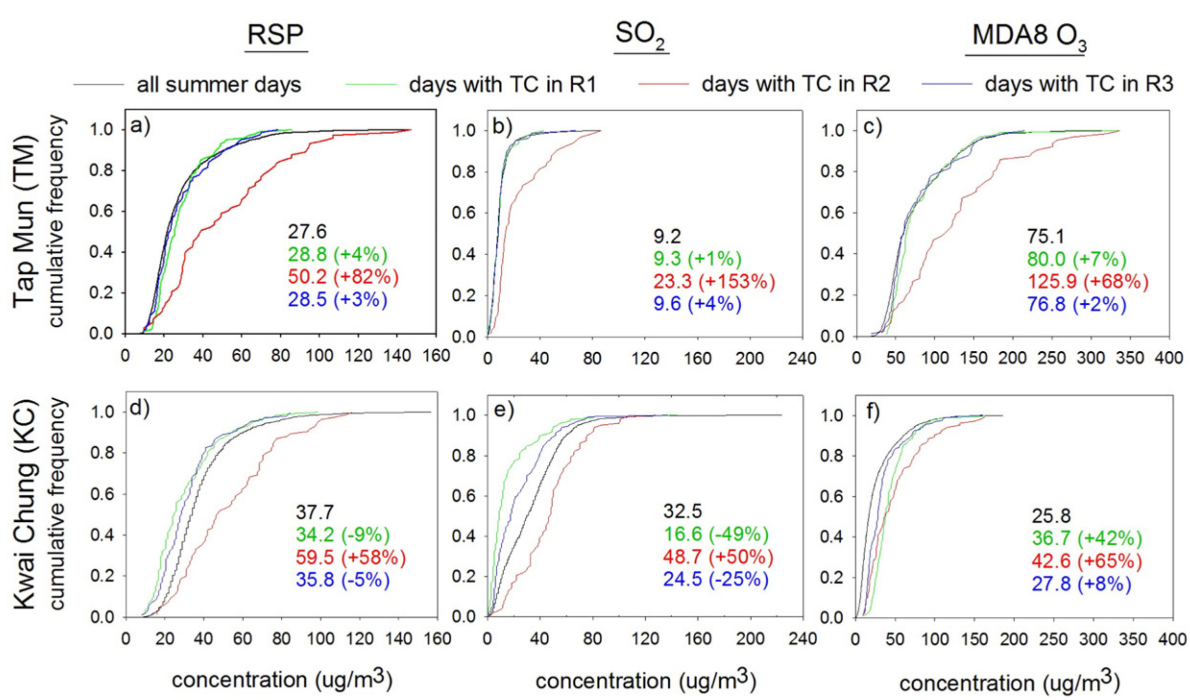

Fig. 4. Cumulative distribution function of daily average RSP, daily average SO_2 and MDA8 O_3 concentrations for all summer days and days with TC in R1, R2 and R3. The values on right hand corner represent the mean concentrations of "all summer days" (black), R1 (green), R2 (red) and R3 (blue) with the percentage differences between "all summer days" and the regions (i.e., R1, R2 or R3) in the parentheses.

those at TM, reported as ~35 μg/m^3 and ~20.6 μg/m^3, respectively, against ~28.7 μg/m^3 and ~9.5 μg/m^3 at TM. For the MDA8 O_3, some increases are found for TCs in R1 and R3 (Fig. 4f), reflecting the influence of the stagnating high-pressure systems at the peripherals on HK (See Table A1 in Appendix for some notable examples). There is not doubt that TC related air quality impact would be influenced by the size and intensity of TC. However, owning to the fact that there were not enough historical TC events on each TC category under each region during the study period, therefore, the impact of TC size and intensity was not studied.

Compared with the average summer day, for days with TCs in R2, the CDFs are clearly shifted to the higher side (to the right) regardless of stations or pollutants, which indicates that poor air quality has been stimulated under TCs in R2. The average mean concentrations of RSP, SO_2 and MDA8 O_3 (average of TM and KC) are reported as ~55.5 μg/m^3, ~36.0 μg/m^3 and ~86.0 μg/m^3, respectively, with the range of +50% to +153% change in the mean concentrations. It is observed that the percentage increase in RSP and SO_2 at TM station is much higher than that of KC station, as the seasonal means of TM station are relatively low at the background station. However, in terms of absolute change in concentration, the values, in fact, are quite similar. For example, for RSP, the mean concentration difference between R2 and "all summer days" is +22.6 μg/m^3 (50.2 μg/m^3 − 27.6 μg/m^3) in TM, and 21.8 μg/m^3 (59.5 μg/m^3 − 37.7 μg/m^3) in KC. This echoes the fact that the pollution enhancement is contributed by the regional air mass that triggers an increase of pollutant levels over large-scale areas across HK. In terms of MDA8 O_3, TM station exhibits much greater enhancement than KC station, as less O_3 scavenging/NOx titration effect is observed at the background station than in the urban station (Chan et al., 1998; Sillman, 1999). Moreover, TM station is a NOx limited area, meaning that a slight increase in NOx would significantly increase O_3 production (HKEPD, 2014; Wang et al., 2017). With the rich precursor emissions (e.g., NOx) from PRD, the O_3 production was intensified (Jiang et al., 2008; Fu et al., 2012), resulting in the mean MDA8 O_3 drastically increasing from 75.1 μg/m^3 to 125.9 μg/m^3.

To better illustrate the impact of air quality induced by TCs at different regions (i.e., R1 to R3), two typhoons were selected from summer 2003 to demonstrate the influence of TCs on local air quality, as shown in Fig. 5a. The first TC (Typhoon Soudelor) formed on June 13 and reached Japan on June 19, while the latter one (Typhoon Imbudo) formed on July 17 and made landfall near Hainan on July 25. The selection of these events was based on the criteria where TCs have passed through at least two of the designated regions (either R3 to R2, or R3 to R1). Fig. 5b and c summarize the daily meteorological parameters with the pollutant concentrations on those TC days at TM station. The color-filled sections (green for R1; red for R2, and blue for R3) signify the days when TCs were passing through the regions. When Typhoon Soudelor first reached R3 on 6/14, the observed impact on air quality due to the change of meteorology was minimal, and the daily NOx, SO_2, RSP and MDA8 O_3 remained at low levels (i.e., <26 μg/m^3 for NOx, 8 μg/m^3 for SO_2 and 36 μg/m^3 for RSP). However, when the TC arrived in R2 on 6/17, there was a clear change of wind direction from southerly or southwesterly to northerly, which brought regional pollutants from PRD to HK, triggering an increase in daily NOx (i.e., 30 μg/m^3), SO_2 (i.e., 33 μg/m^3), and RSP (i.e., 82 μg/m^3) on both 6/17 and 6/18. The increase of temperature and solar radiation with abundance of precursors (e.g., NOx) is conducive to the formation of secondary pollutants (i.e., O_3); it resulted in an increase in MDA8 ozone at TM station from

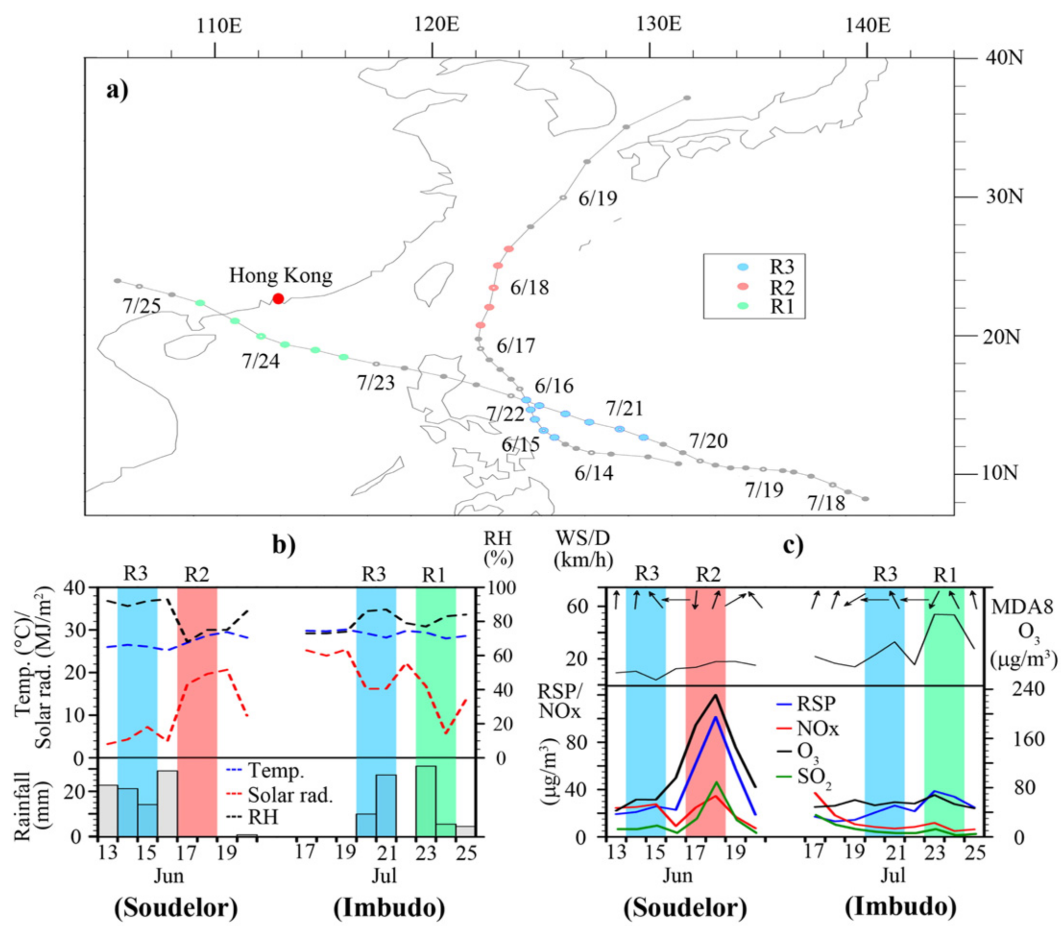

Fig. 5. Selected TC examples: a) TC tracks; b) meteorological parameters; and c) pollutant concentrations with wind data.

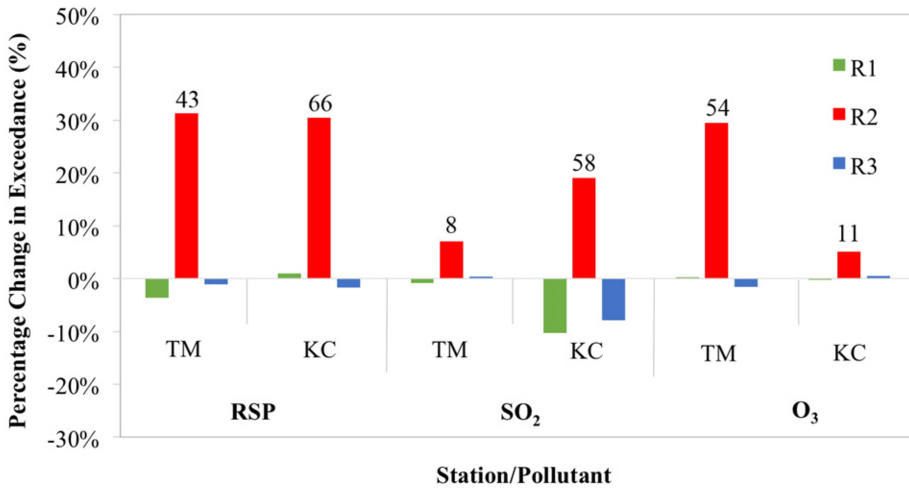

Fig. 6. Percentage change in exceedance frequencies of WHO AQG limits (daily avg. RSP > 50 μg/m^3, daily avg. SO_2 > 50 μg/m^3 (Interim target-2), and MDA8 O_3 > 100 μg/m^3) in the summer months. The numbers on top of the red bar show the extra exceedance when TCs are in R2.

96 μg/m^3 on 6/16 to 231 μg/m^3 on 6/18. Compared with Typhoon Souderlor, Typhoon Imbudo was also formed in WNP. However, it didn't pass through R2, but rather it went through the SCS to reach R1. When the TC entered R1 on 7/23, a slight increase in RSP (i.e., from 22 μg/m^3 to 39 μg/m^3), SO_2 (i.e., from 5 μg/m^3 to 8 μg/m^3), and NOx (i.e., from 8 μg/m^3 to 12 μg/m^3) was observed. This increase of pollutant concentrations may be attributed to the easterly or northeasterly wind that carried the lightly polluted air from eastern Guangdong.

In terms of policy implication, Fig. 6 shows the frequencies of exceedance of WHO air quality guidelines (AQG) for the difference between "all summer days" and days with TCs in each region. Compared with "all summer days", the exceedance frequencies for those days with TCs in R2 are strongly increased for all three pollutants at both stations, while the exceedance frequencies for days with TCs in R1 and R3 are mostly unchanged or decreased. Similar trends are also observed between "all autumn days" and days with TCs in each region. (See Appendix Fig. A1). In general, the percentage increase in exceedance at TM station is usually lower than at KC station for SO_2, while it is higher for MDA8 O_3. This agrees with the earlier findings on the relationship of concentration difference for those two stations. Overall, the increase (average of TM and KC) in RSP, SO_2 and MDA8 O_3 during summer (autumn) with TCs in R2 is reported as 31% (20%), 13% (6%), and 17% (9%), respectively. This result confirms that TCs in R2 have a detrimental impact on Hong Kong air quality, regardless of the seasons (i.e., summer and autumn).

3.3. Interdecadal comparisons of pollution trends under the influence of TCs

Based on the TC data from HKO, the total number of TCs found in the WNP and the adjacent seas bounded by the Equator, 45°N, 100°E, and 180°E, and those found in R1, R2, and R3 in the first and second epochs for the summer months are summarized in Table 1. Comparing epoch 2 with epoch 1, there had been an overall decrease of approximately 9% in the total number of TCs (from 144 to 131). It is observed that the number of TCs found in R1 and R3 also dropped by about 15% (from 39 to 33), and 8% (from 38 to 35), while the number of days in R1 and R3 dropped by 10% (from 87 to 78 days) and 32% (95 to 65 days), respectively. Conversely, both the number of TCs and number of days in R2 has a noticeable increase of about 23% (from 35 to 43 days), and 50% (from 62 to 93 days), respectively. The increase of TCs occurrence in R2 in the second epoch certainly produces a negative impact on HK air quality, as demonstrated in Section 3.2. Moreover, the increase of average TC residence time (from 1.8 to 2.2 days/event) in R2 may also lengthen the time of air pollution episode. A similar trend of increase on both number of TCs (from 49 days to 68 days) and TC residence time (from 2.5 to 2.8 days/event) in R2 is also observed in the autumn months (see Appendix Table A2). It is expected the air pollution episode will intensify due to this observed TC track change if the phenomenon continues.

To further understand the impacts on air quality due to the increase of TCs in R2, we have selected SO_2 and O_3 as a probing species to better evaluate their air quality impacts. Fig. 7 shows the trend of mean SO_2 concentrations for "all summer days" and R2. Both KC and TM stations on days with TCs in R2 show a clear increasing trend from 1990 to 2005 while a downward trend is observed after 2005. The reduction of SO_2 in 2005 was attributed to the massive installation of flue-gas desulfurization (FGD) system in the power generation sector over PRD under the China's 11th Five-Year Plan (2005 to 2010) (Lu et al., 2010). As mentioned before, air quality impact with TCs in R2 is mainly caused by long-range transport from PRD, therefore, the reduction of SO_2 concentration is more pronounced with TCs in R2 than the "all summer days". In terms of decadal change of SO_2, a lower enhancement is observed in the first epoch ($38.4 - 30.0 = 8.4$ μg/m^3) than in the second epoch ($51.1 - 34.8 = 16.3$ μg/m^3) with TCs in R2. This was attributed to the difference in magnitude of the overall SO_2 emissions in PRD on those two periods (emission in first epoch is much greater than that in second epoch). It is expected that the impact of TCs on SO_2 pollution in HK will eventually be mitigated if SO_2 emissions in China continue to decrease.

Table 1
Impact of track change from the first epoch (1991–2000) to the second epoch (2001 − 2010): Change in number of TCs and change in number of days with TCs in each region (Summer - May to August).

Epoch	Period	All TCs	R1		R2		R3	
			Number of TC/Number of days	Avg. days	Number of TC/Number of days	Avg. days	Number of TC/Number of days	Avg. days
1	1991–2000	144	39/87	2.2	35/62	1.8	38/95	2.5
2	2001–2010	131	33/78	2.3	43/93	2.2	35/65	1.9
–	% change	−9%	−15%/−10%	+6%	+23%/+50%	+22%	−8%/−32%	−26%

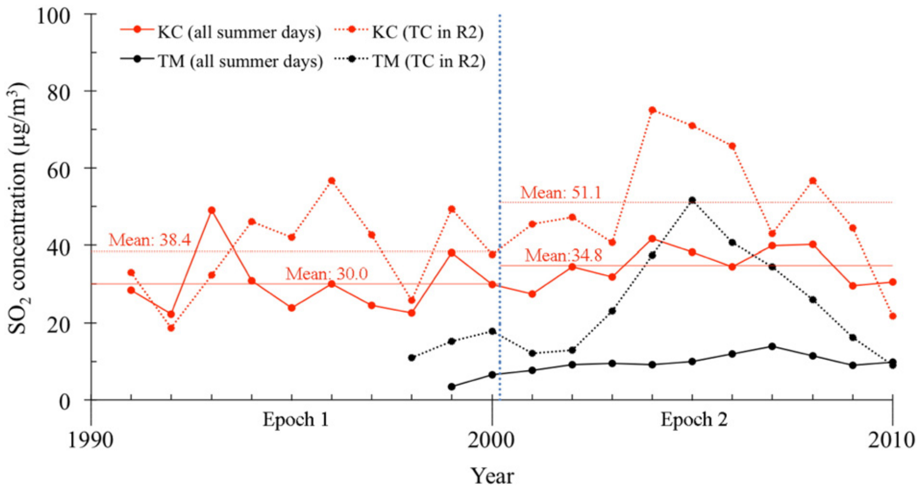

Fig. 7. Mean SO_2 concentrations for all summer days and days with TCs in R2.

Fig. 8 shows the mean O_3 concentrations for "all summer days" and days with TCs in R2. The mean O_3 concentration in KC station in the second epoch (23.3 $\mu g/m^3$) is slightly higher than that in the first epoch (19.8 $\mu g/m^3$). Although there are fluctuations reflecting the variation of the impact of TCs in R2 in different years, no downward trend can be found at the end of the second epoch as in the case for SO_2. The mean O_3 concentrations for the days with TCs in R2 show an increasing trend at the rate of approximately 0.5 $\mu g/m^3$ per year at KC station and 2.6 $\mu g/m^3$ per year at TM station. These values are slightly higher than the rate of increase for the "all summer days" (i.e., 0.3 $\mu g/m^3$ and 0.4 $\mu g/m^3$ per year at KC and TM stations, respectively). It is also higher than 0.54 to 0.76 $\mu g/m^3$ per year reported by Lee et al. (2014). These results reveal that the impact with TCs in R2 on O_3 concentrations has been increasing from 1991 to 2010 and will become more intense if the trend continues. One of the possible causes of the escalating impact is related to urban heat island effect and global warming, as summer air temperatures in HK reach even higher levels under stagnating high pressure and intense sunlight when TCs are in R2. The increase of temperature triggers an increase in roadside NOx, evaporative (e.g., formaldehyde) VOCs from gasoline vehicles, and biogenic VOCs from vegetation, which encourage the formation of ozone (Lee et al., 2014; Lam et al., 2011). As TM station is much more photochemically sensitive than KC station from the change of solar radiation and precursor concentrations (i.e., NOx), this resulted a higher rate of increase in ozone concentration at TM station (Ling and Guo, 2014).

4. Conclusions

Based on the changes in TC track density in May to October from epoch 1 (1991–2000) to epoch 2 (2001–2010), an analysis has been performed focusing on the impact of TCs in three regions of interest (R1 in the SCS, R2 in the vicinity of Taiwan, and R3 in the Philippines Sea) on the air quality of Hong Kong. It has been found that from epoch 1 to epoch 2, the number of TCs in R2 increased by 22% (from 55 to 67), while the number of TCs in R1 and R3 decreased by 22% (from 60 to 47) and 8% (from 61 to 56), respectively (See Table A3). These results agree with the prevailing shift of TC activities towards the vicinity of Taiwan in association with the WNP-East Asian climate change (Wu et al., 2005; Tu et al., 2009), and it has been suggested that this track change may continue to prevail for a few decades (Wu and Wang, 2004; Wang et al., 2011).

The air quality impact of TCs in the three regions is studied by comparing the RSP, SO_2 and O_3 concentrations from two of the HKEPD monitoring stations (TM – rural station, and KC – urban station) in summer. It has been found that on days with TCs in R2 (near Taiwan), an obvious increase of pollutant concentrations is observed in both the remote and urban areas (82% and 58% for RSP, 153% and 50% for SO_2 and 68% and 65% for O_3, in TM and KC respectively). The frequencies of exceedance of WHO AQG limits are also increased for days with TCs in R2 (similar result was also found in autumn). These observations show that the impact of TCs on local air quality is highly related to the TC position and the

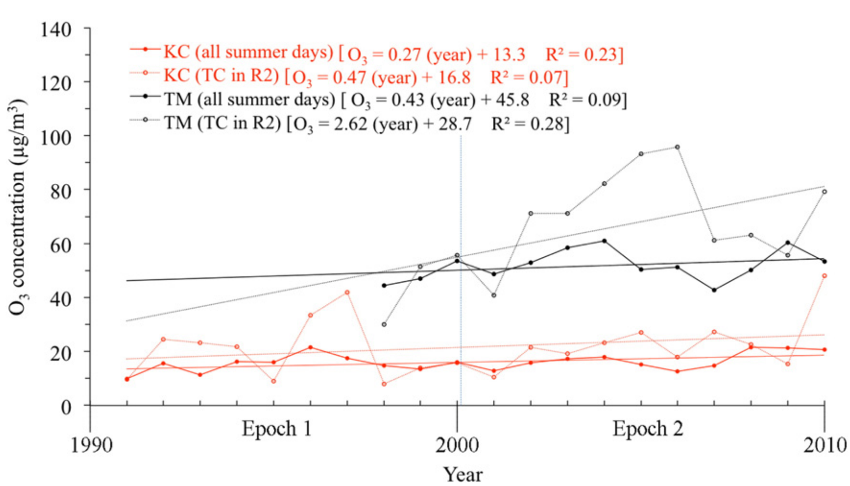

Fig. 8. Annual mean O_3 concentrations for all summer days and days with TCs in R2; the straight lines correspond to the linear regression fit for each case.

Fig. 9. Summary of conceptual relationship.

adverse effects are highest when they are in the vicinity of Taiwan. The increased number of TCs in this region resulted in higher impact on Hong Kong's air quality in the decade after 2000, and it can be projected that the impact of TCs will be intensified if the prevailing track change towards Taiwan persists due to global warming or climate change. A summary of the conceptual model for the relationship between TC track change and pollution episode is shown in Fig. 9.

From the intra-annual variations, it has been found that the elevated concentrations of primary pollutants such as SO_2 on TC-affected days are highly correlated with the emissions in China and PRD due to regional transport of air pollutants by the northwesterly wind. The impact of TCs on SO_2 concentrations escalated after 2000 during the economic boom in PRD and started to decline around 2005. It can be expected the impact on SO_2 concentrations will continue to diminish with reduced SO_2 emission in PRD. For the secondary pollutant O_3, the impact of TCs is related to the meteorological conditions for active photochemical reactions as well as regional transport of O_3 and its precursors. When TCs are in the vicinity of Taiwan, formation and accumulation of O_3 are accelerated by conditions of stagnation, high temperature, and intense sunlight under the high pressure systems at the TC peripherals, and at the same time supplemented by the light northwesterly wind that brings in O_3 and O_3 precursors from PRD. As a result, the increase of O_3 concentrations is particularly pronounced. Furthermore, the analysis of yearly O_3 change shows that the mean O_3 concentrations of the days affected by TCs near Taiwan are increasing at a higher rate than the average summer concentrations in both the remote site (i.e., TM) and the urban area (i.e., KC). It is likely that the prevailing TC track change towards the Taiwan region will lead to more severe summer O_3 episodes to HK in the future.

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Appendix A

Table A1
Top ten MDA8 O_3 concentrations at Tap Mun (TM) from 1998 to 2010.

Rank	MDA8 O_3 ($\mu g/m^3$)	Year	Month	Day	TC name	TC position	TC intensity[a]
1	337	2006	8	8, 9	Bopha	R2, R1	TS/TD
					Saomai	R2	T
2	320	2008	7	28	Fung-wong	R2	T
3	277	2005	7	18, 19	Haitang	R2	T
4	260	2009	7	10	Soudelor	R1	TD/TS
5	257	2005	8	31	Talim	R2	T
6	251	2006	7	24, 25	Kaemi	R2	T/STS/TS
7	248	1999	8	19, 20	Sam	R3, R1	TD/STS/T
8	243	2007	5	17	Yutu	R3	STS/T
9	231	2003	6	18	Soudelor	R2	T
10	225	2004	6	9	Conson	R2	T

[a] T.D. - Tropical Depression has maximum sustained winds of <63 km/h; T.S. - Tropical Storm has maximum sustained winds in the range 63–87 km/h; S.T.S. - Severe Tropical Storm has maximum sustained winds in the range 88–117 km/h, and T - Typhoon has maximum sustained winds of 118 km/h or more.

Table A2
Impact of track change from the first epoch (1991–2000) to the second epoch (2001–2010): Change in number of TCs and change in number of days with TCs in each region (Autumn - September to October).

Epoch	Period	All TCs	R1		R2		R3	
			Number of TC/Number of days	Avg. days	Number of TC/Number of days	Avg. days	Number of TC/Number of days	Avg. days
1	1991–2000	105	21/50	2.4	20/49	2.5	23/60	2.6
2	2001–2010	81	14/30	2.1	24/68	2.8	21/45	2.1
–	% change	−23%	−33%/−40%	−10%	+20%/+39%	+16%	−9%/−25%	−18%

Table A3
Impact of track change from the first epoch (1991–2000) to the second epoch (2001–2010): Change in number of TCs and change in number of days with TCs in each region (May to October).

Epoch	Period	All TCs	R1		R2		R3	
			Number of TC/Number of days	Avg. days	Number of TC/Number of days	Avg. days	Number of TC/Number of days	Avg. days
1	1991–2000	249	60/137	2.3	55/111	2.0	61/155	2.5
2	2001–2010	212	47/108	2.3	67/161	2.4	56/110	2.0
–	% change	−15%	−22%/−21%	0%	+22%/+45%	+19%	−8%/−29%	−23%

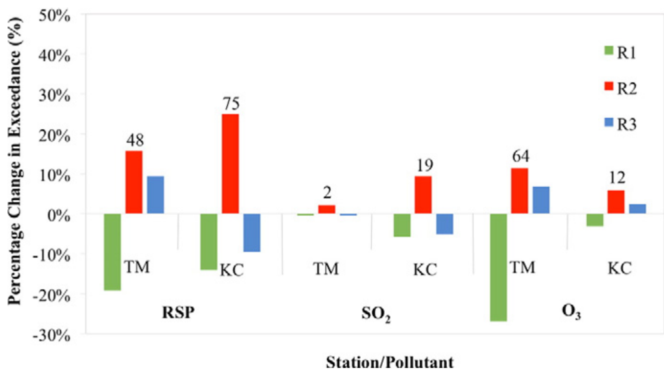

Fig. A1. Percentage change of exceedance frequencies of WHO AQG limits (daily avg. RSP > 50 μg/m^3, daily avg. SO_2 > 50 μg/m^3 (Interim target-2), and MDA8 O_3 > 100 μg/m^3) in the autumn months. The numbers on top of the red bar show the extra exceedance when TCs are in R2.

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.08.100.

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